Conference Summary: The Cosmic Agitator – Magnetic Fields in the Galaxy

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Subject headings: magnetic fields — MHD — masers — polarization — turbulence — instrumentation: interferometers — instrumentation: polarimeters — techniques: polarimetric — surveys — stars: formation

1. INTRODUCTION

The very first observations of the galactic magnetic field were made in 1948, independently by William Hiltner of Yerkes Observatory and by John Hall of Amherst College and the U. S. Naval Observatory. Both observed polarization of starlight, and both published their results in the journal *Science* in 1949. In 2008 Mar 26-29, about 80 astronomers met in the scenic city of Lexington, Kentucky to celebrate 60 years of observations of the interstellar magnetic field, and discuss and debate relevant theoretical studies. The conference was formally titled: "The Cosmic Agitator: Magnetic Fields in the Galaxy." A coincidental reason for the conference was to celebrate the 60th birthday of Thomas H. Troland and honor his contributions to the observations of magnetic fields in the interstellar medium. Troland's birthday provided a serviceable excuse to celebrate magnetic fields with a product that goes back much further even than Hiltner and Hall — fine old Kentucky bourbon from Buffalo Trace Distillery. Contrary to popular imagination, "buffalo trace" is not a waste product from the animal. Instead, it is a wide path established by migrating buffalo that were prevalent in Kentucky centuries ago. The current distillery is built on part of what was once such a buffalo thoroughfare.

In this paper we present a summary of the conference, drawing primarily from material in the slides prepared for the Conference Summary by one of us (Carl Heiles). It is "a necessarily restricted view" — restricted by the 30-minute time slot provided to Heiles for

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the summary, and the number of pages we would have to fill if we tried to summarize the entire array of wonderful talks and posters. Interested readers may navigate to the conference web site[1], where all the presentations have been posted (except for a few presentations whose authors have requested that their talks not be included on the website).

2. MAJOR ISSUES: A NECESSARILY RESTRICTED VIEW

The following is an overview of the issues covered at this conference.

- **Observations:** There is an overwhelming detail and variety in the observations because of great technical advances over the past 40 years, at optical, infrared, millimeter, and centimeter wavelengths. A substantial array of measurements of the perpendicular component of the magnetic field from linear polarization observations and the parallel (line-of-sight) component of the magnetic field from circular polarization observations is now available.

- **Theory:** Again, there is an overwhelming amount of theoretical work that addresses magnetic fields due to substantial advances in computational capability in the past decade.

- **Masers:** Four maser transitions (OH, H_2O, CH_3OH, SiO) allow measurements of the magnetic field in star forming regions, supernova shocks and late-type stars in our Galaxy, and even in the extragalactic environment.

- **Some specific issues:** The morphology of the global Milky Way field remains unclear. Other specific issues addressed relate to the containment of overpressured slabs (Galactic and extragalactic), grain alignment physics, and the theory and observation of ambipolar diffusion.

- **Instrumentation:** Without instrumentation, of course, none of the above would be possible. Several speakers at the conference addressed directly the scope and opportunities from new, upcoming, and planned telescopes.

[1] http://thunder.pa.uky.edu/magnetic/

3. LARGE-SCALE FIELDS IN THE MILKY WAY

There appear to be unresolved issues regarding the large scale magnetic field of our Milky Way Galaxy. Jin Lin Han reported that the large-scale magnetic field in our Galaxy reverses from arm to interarm. Using rotation measures (RMs) for 223 pulsars, together with data from the literature, Han et al. (2006) found evidence for large-scale counterclockwise fields (viewed from the north Galactic pole) in the spiral arms interior to the Sun. However, in interarm regions, they found that the large-scale fields are clockwise, and proposed that the large-scale Galactic magnetic field has a bisymmetric structure with reversals on the boundaries of the spiral arms. On the other hand, Marijke Haverkorn reported that the Galactic magnetic field reverses from arm to arm. Using new Faraday RMs for 148 extragalactic radio sources behind the southern Galactic plane together with all available extragalactic and pulsars RMs in this region, Brown & Haverkorn et al. (2007) generated a simple model for the magnetic field in the fourth quadrant of the Milky Way. They find that the magnetic field in the fourth Galactic quadrant is directed clockwise in the Sagittarius-Carina spiral arm (as viewed from the north Galactic pole), but is oriented counterclockwise in the Scutum-Crux arm (e.g., see Fig. 4 in Brown & Haverkorn et al. 2007). Are different conclusions being obtained from the same data? Clearly, more needs to be done about this important topic; in particular, more data on the first quadrant is required.

Han et al. (1997) found that the RMs for extragalactic sources reveal a striking antisymmetric pattern about the Galactic plane; this is also shown in the RMs of nearby pulsars at high latitudes. Such a pattern is consistent with the field configuration of an A0 dynamo. Ann Mao and collaborators have undertaken a study of the vertical and horizontal components of the magnetic field above and below the location of the Sun via a 1.4 GHz survey of about 1000 polarized sources ($|b| > 77°, L > 4$ mJy). They find a vertical field of 0.10 ± 0.02 μG. Heiles adds the following, which he considers the most important point: the field direction from the RM fit *agrees* with the field orientation from the stellar polarization!

4. SMALLER SCALE MAGNETIC FIELDS

Magnetic fields on smaller scales are related to those on larger scales and the outer turbulence scale. Giles Novak discussed dust polarimetry measurements of magnetic field morphology in molecular clouds. He showed that the field orientation in four clouds is parallel to the Galactic plane (Li, . . . , Novak et al. 2006). By comparing SPARO observations of large-scale giant molecular cloud fields with simulations of turbulence, he and his collaborators inferred that the magnetic energy is comparable to the turbulent energy. Marijke Haverkorn reported that energy injection in the spiral arms occurs by multiple mechanisms

on size scales ranging down to pc, not only by single and multiple supernovae at $\sim$100 pc scales as usually assumed. The interarm regions do show additional turbulence driving sources up to $\sim$100 pc. Energy input in the spiral arms is likely dominated by H II regions, stellar winds, or protostellar outflows.

5. THEORY AND SIMULATIONS: NEW DEVELOPMENTS

Magnetic fields have important dynamical effects from the diffuse to the dense ISM, as reported by Eve Ostriker. Ostriker discussed the many contributions from magnetic effects suggested by theory; for example, magnetic tension and differential rotation produce turbulence via magnetorotational instabilities, etc., and reviewed recent numerical results related to them.

Zhi Yun Li discussed magnetic braking and protostellar disk formation. He noted that the formation of rotationally supported disks is not guaranteed, and magnetic decoupling together with some other causal agent is required for disk formation in cores with a realistic mass-to-flux ratio (λ). Simulations show that ambipolar diffusion in its simplest form does not enable disk formation for realistic levels of cloud magnetization and cosmic ray ionization.

Ellen Zweibel discussed ambipolar diffusion in a turbulent medium, and reported that in a turbulent, weakly ionized medium magnetic flux is transported relative to the neutrals via small scale ion-neutral drifts depending on the eddy rate. This enhanced diffusion contributes to the flat B-field vs. density relation in the diffuse ISM and it may account for relatively weak fields in molecular clouds.

William Henney discussed the effect of magnetic fields on the evolution of H II regions. He showed an eerily realistic simulation of an H II region with magnetic fields (the image is available in Henney's posted talk on the conference website), which gives an irregular H II region boundary which is also permeable — thus providing photon escape paths to form the Warm Ionized Medium (WIM).

Daniel Price discussed the effect of magnetic fields on ISM morphology. Even at high β where the magnetic energy density is small compared to thermal and turbulent energy densities, magnetic fields delay and suppress star formation. Moreover, it appears that magnetic nature loves a vacuum! Strong magnetic fields ($\beta < 1$) lead to large scale voids, anisotropic turbulent motions and column density striations along field lines due to streaming motions in the gas. Some of this is demonstrated in existing ^{12}CO observations of Taurus (Goldsmith et al. 2007; figure available in Price's presentation on the Conference website).

6. PRESSURE OR LIFETIME PROBLEMS

Tom Troland reported on Zeeman observations of the Orion Veil. The basic geometry of the veil from Abel et al. (2004) is that of two neutral hydrogen sheets (e.g., see their Fig. 2) that give rise to components A and B in absorption. Troland reported that Component A is dominated by magnetic energy whereas component B is in approximate equipartition. In one possible scenario, component B lies closer to the trapezium stars, and has an associated H II region that absorbs the momentum of the stellar UV radiation. This compresses component B, thereby increasing the magnetic field and, consequently, the magnetic pressure. The magnetic pressure in component B resists the momentum of the absorbed stellar radiation, putting it in "hydrostatic" equilibrium with the stellar radiation field.

Art Wolfe reported on the detection of an unusually strong magnetic field of $B_{los} = 83.9 \pm 8.8\mu G$ in a damped Lyman-α system at $z = 0.7$ toward 3C 286. The neutral gas ($n_e/n < 2 \times 10^{-4}$) in which this effect has been detected has an extent of over 280 pc, and is quiescent, highly magnetized ($\lambda_n = 2\pi G^{1/2}\Sigma/B_{plane} = 0.04$), metal-poor and nearly dust-free. Its star formation rate per unit area is less than that of our Galaxy. The detection at $z = 0.7$ of $B_{los} = 83.9$ μG averaged over 200 pc scales is completely unexpected: Dynamo theory predicts B-fields to be weaker, not stronger, in the cosmological past. Such strong fields are found in star-forming regions near centers of galaxies, but the Star Formation Rate in DLA-3C286 is low. Since magnetostatic equilibrium is not satisfied, a B-field of $\sim$5 μG may be enhanced to 100 μG by a merger-induced shock. Therefore, an open question is whether a dynamo can build up $\sim$5 μG fields in the 4-5 Gyr age of the disk.

Heiles notes that both the above systems (the Orion Veil and the DLA toward 3C 286) appear to present identical problems: a sheet of material, highly overpressured, with no apparent means of containment. Telemachos Mouschovias noted that the magnetically overpressured region of the Orion Veil may be confined by the gravitation of the Orion Molecular Cloud as a whole.

7. MASERS

Following the presentation by William Watson on masers as a probe of magnetic fields, several speakers reported on observations of masers in a variety of environments. Crystal Brogan described the observations of 1720 MHz OH masers to trace supernova shocks, Anuj Sarma reported on observations of H_2O masers in star forming regions, Wouter Vlemmings reported on methanol masers — a new addition to the Zeeman family, Tim Robishaw reported on Zeeman detections in OH megamasers, and Athol Kemball on SiO masers near

AGB stars.

Brogan reported simple Zeeman patterns in 1720 MHz OH masers, yielding $B_\theta = 0.2-5$ mG and weak ($\sim 10\%$) linear polarization. The magnetic pressure is of the order of the shock ram pressure, and the magnetic field follows the $B \propto (\Delta v)\, n^{0.5}$ (Basu relation) *if* the CO line width is used. Moreover, the B-field is stronger with higher resolution! Brogan posed the following (open) questions on this topic: What are the detailed properties of the polarization and can we distinguish between theoretical models? How is the maser flux distributed on small size scales and what are the brightness temperatures? Does the B-field really increase with higher resolution (which might be indicative of more tangled B-fields on larger size scales)? Alas, using VLBA observations with a spatial resolution of a few 10s of milliarcseconds, Brogan finds that all of the apparent increase in field strength with resolution can be explained by spectral blending effects from multiple maser spots at slightly different velocities. Brogan's comments on the angle made by the magnetic field provided a close interface between observations and detailed maser theory described in William Watson's presentation.

Methanol masers are the newest addition to the Zeeman family. Wouter Vlemmings mentioned that they are radiatively pumped in pre-/post-shock regions by IR emission from shocks. Methanol masers originate in regions where high CH_3OH densities are generated by evaporation from dust grains, and are often found in similar regions as OH. Vlemmings reported significant detections in 17 of 24 star forming regions with line-of-sight field strengths of 12 mG. Field reversals are also detected in two sources. Heiles adds, however, that what is commonly referred to as reversals are more likely to be small changes in angle to the plane-of-the-sky. The line-of-sight field directions from Vlemmings' work are consistent with OH maser observations, and therefore indicative of the Galactic magnetic field direction.

Tim Robishaw reported on the detection of magnetic fields in 5 ULIRGs, via observation of the Zeeman effect in OH megamasers. These are the first extragalactic Zeeman splitting detections in emission lines; the only previous extragalactic Zeeman detection was in H I absorption lines in the high-velocity cloud around Perseus A (Kazes et al. 1991; Sarma et al. 2005). The detected B-fields are similar to Galactic sites of OH masers, which is not surprising since conditions in regions of massive star formation are similar to those in the Milky Way. Moreover, the detected B-fields are consistent with magnetic fields in ULIRGs inferred from minimum energy and equipartition considerations.

8. TURBULENCE, AMBIPOLAR DIFFUSION AND OTHER ISSUES

Alex Lazarian discussed the current state of grain alignment theory and its implications. Lazarian remarked that polarization from aligned dust allows us to trace magnetic fields if we understand grain alignment. For example, some apparent reversals in field direction may be due to radiative torques (RATs).

Martin Houde seems to be directly detecting ambipolar diffusion, via a difference in line widths between coexistent ionic and neutral species. Ambipolar diffusion and turbulence were discussed by a number of theorists, including Mordecai-Mark Mac Low, Telemachos Mouschovias, Shantanu Basu, Fabian Heitsch, and Konstantinos Tassis. For the "turbulence-community" Mac Low stated that the bottom line is that magnetic fields are important, but they don't dominate molecular core formation. Instead, star formation is regulated by turbulent flows modulated by magnetic fields. Shantanu Basu discussed the issue of core formation due to magnetic fields, ambipolar diffusion and turbulence.

Many new and impressive results on dense and star-forming regions were reported by Roger Hildebrand, Brenda Matthews, Giles Novak, Dick Crutcher, and Ramprasad Rao. Based on (ongoing) statistical analysis of the full set of Zeeman results presented in Crutcher (1999), Crutcher concluded that the increase in the mass-to-flux ratio from the envelope to the core required by ambipolar diffusion is not seen. However, Telemachos Mouschovias questioned whether this result is truly inconsistent with the ambipolar diffusion-driven models of star formation. He suggested that a more careful comparison of theory and observations is warranted.

A number of graduate students gave impressive talks and poster presentations, signalling that the next generation is ready and willing to continue on the path blazed by the seasoned pioneers and expand the frontiers of knowledge. Sui Ann Mao's result on the magnetic field above and below the Galactic plane, and Tim Robishaw's detection of the Zeeman effect in ULIRGs have already been discussed above. Talayeh Hezareh reported on a method to simultaneously calculate the Cosmic Ray Ionization Rate and Fractional Ionization in DR21(OH).

9. INSTRUMENTATION

The future looks bright for instrumentation, if funds allow. Optical and IR polarization can now be done with CCDs, instead of single-pixel polarimeters! Antonio Mario Magalhaes reported on a proposed 2-3 meter robotic telescope for starlight polarization, and he has it all designed! Dan Clemens discussed IR polarization, and informed us that the Galactic Plane

Infrared Polarization Survey (GPIPS) is up and running, and will be about 50% complete after the current season. When completed, it is expected to yield about 400,000 new H-band stellar polarizations across 76 square degrees of the inner Galactic Plane. Darren Dowell made the case for an instrument performing far-IR polarimetry from space, pointed out that no planned mission seems to have considered this need, and stressed the need to start campaigning for a polarimeter in space. Brenda Matthews examined the prospects for dust linear polarization measurements with SCUBA-2; Heiles remarked that SCUBA-2 is fantastic! Following his report on polarimetric studies of interstellar turbulence, Roger Hildebrand reiterated that SOFIA needs a polarimeter.

Radio and mm wavelengths also offer great promise. Rick Perley predicted that EVLAs polarization capability will ovewhelm us. Dick Plambeck revealed the mouth-watering prospects of CARMAs upcoming polarization capability. Ramprasad Rao showed how the SMA is already a fantastic polarimeter! Al Wooten described how ALMA will be the ultimate mm-wave polarimeter when it arrives.

10. SUMMARY

Just as the buffalo grazing through Kentucky left behind a site that would fulfill the Bacchanalian aspirations of generations of humanity, so it is our hope that the hordes of astronomers trekking through the Bluegrass state will leave behind not only a memory of days spent in great enjoyment and wonder at cosmic mysteries, but a firm foundation on the relevance of the magnetic field to the Universe upon which to build in future. This conference showed us how far we have come from the days of Hiltner & Hall, and gave us an inkling of how far we have to go. The future appears to be full of promise, and on that note of hope we shall end our summary of the proceedings, thereby allowing thirsty astronomers to return to oversized bottles of Kentucky bourbon which were (hopefully) not confiscated at airport check points!

We thank all the participants who traveled to the Bluegrass state from near and far for a very stimulating and wonderful conference. Thanks are due to support staff at the University of Kentucky (UK): Eva Ellis (Dept. of Physics & Astronomy) and Richard Mullins for responding swiftly and efficiently to all requests for assistance, and to Clay Gaunce of UK Tech Support and other members of the Tech Support team for assistance beyond the call of duty. We would like to acknowledge the support provided by the UK College of Arts & Sciences Graduate School, UK Department of Physics and Astronomy and the Center for Computational Sciences, UK. We have used extensively the NASA Astrophysics Data

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